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Fine tunings and quark masses: Phenomenology of multiple domain theories

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Abstract
This talk describes some of the consequences for particle phenomenology of the hypothesis that the physical parameters may vary in different domains of the universe.

1. Introduction

This talk‡ is a mini-review of a possible pathway in the search for the fundamental theory. This approach is quite distinct from the usual directions taken in searching for new theories, and hence may appear a bit odd at first. However, it may also lead to new possibilities and could prove useful.

The basic hypothesis is that there exist different domains in the universe where (at least some of) the parameters of the underlying theory can take on different values. We would live entirely within one such domain and, under the assumption of inflation, we would not see any variation within this domain nor would we have access to other domains. This multiplicity of parameters and domains is in strong contrast with the usual assumption that if we work hard enough, we can uncover the theory whose unique ground state determines our world.

This may not be as crazy as it sounds at first. An effect like this can occur in chaotic inflation[1], where scalar fields can get frozen at random values if their potential is flat enough. It is also a conceivable outcome in string theory where there are continuous families of ground state solutions, and we have little insight as to how one ground state is selected or preserved. However, it is enough to have occurred in one physical theory, such as chaotic inflation, to need to take the general idea seriously as a possibility.

The idea is also not as empty as it first sounds. Clearly it tell us that the some specific parameters that we see may not be uniquely predictable. However, as described below, there is still some information contained in those parameters. Moreover, the hypothesis can suggest that certain problems, such as fine tuning problems, are less serious than they first appear and thus motivate new approaches to the exploration of fundamental theories.

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2. Weinberg and the cosmological constant

Weinberg has made a physical calculation that is relevant for this hypothesis[2, 3]. He notes that for most values of the cosmological constant the universe is extreme and sterile, either living an extremely short time of order the Planck scale or expanding too fast for matter to ever clump. He calculates the range of the cosmological constant that allows galaxies to clump, and finds that it very small. This then leads to a natural constraint on our domain - out of all possible domains we would only find ourselves in a domain such that matter clumps. In turn, this leads to a consistency check on whether it is reasonable to think that this constraint is the main explanation for the smallness of the cosmological constant or whether other explanations must be sought. If the observed value of the constant is very much smaller than the allowed range, we would expect that another mechanism is needed to make it so small. However if the value is typical of the range then no extra explanations are needed within the class of multiple domain theories.

The actual range and the mean value have been estimated[3], and the interesting feature is that the newly observed value of the cosmological constant is reasonably typical of the viable range. A zero value of the cosmological constant is already extremely difficult to understand theoretically. A non-zero value of this extremely tiny magnitude is even harder to understand by a dynamical mechanism. If the observed cosmological constant is correct, it finds a natural home in multiple domain theories and, by itself, is a reason to take this hypothesis seriously.

There are two recent developments related to Weinberg's result. Tegmark and Rees[4] have pointed out that the initial strength of density perturbations, Q, also enters into the calculation of gravitational clumping, They show there is a limited viable region in the two-dimensional space of Q and Λ, thus generalizing Weinberg's constraint. In addition, Garriga and Vilenkin[5] has pointed out that Weinberg's assumption of a flat weight for the distribution in the cosmological constant may not hold in various Higgs models, and that this weight can lower the mean viable value. Both of these represent interesting developments of Weinberg's original calculation, and do not diminish the attractiveness of the general idea.

3. Fine tuning of the the Higgs mass parameter

The other great fine-tuning problem that motivates particle physicists is that of the Higgs vacuum expectation value. A similar constraint can be calculated in this case. Here the assumption is that the existence of complex elements is a natural constraint for the domain that we find ourselves in. That is, domains in which there is only one element do not have the complexity needed for life of any sort. My collaborators and I[6] have tried to estimate this viable range for the Higgs mass parameter, under the assumption that all of the other dimensionless parameters of the Standard Model do not change.

The basic physics is that the Higgs vev controls quark masses and, if the quark masses increase a modest amount, complex matter ceases to be exist in the universe. The first problem is the unbinding of deuterium as the pion gets slightly heavier. Deuterium is needed in all of the mechanisms for element production. However, a more serious constraint occurs at a vev about five times that observed, when the neutron becomes heavier than the proton by enough that all nuclei are unstable to decay to free protons. This leaves a universe of protons only. At much larger values of the vev, the Δ^{++} becomes the only element but there is still not enough complexity for life. Thus out of the whole range for the Higgs vev, the observed value is reasonably typical of the viable range.

This was done under the assumption that the other constants have been held fixed. However, it is likely to be a reasonably robust conclusion. The most general way to state the result is that the existence of complex elements requires the weak scale and the QCD scale to overlap. The quark masses are manifestations of the weak scale. In the real world, some of these masses are below the QCD scale and some are above. Complex elements only arise through the interplay of the QCD scale and the quark masses, which allows more than one hadron to have masses close enough to each other to provide variation in the nuclei. (Electromagnetic effects at order $\alpha\Lambda_{QCD}$ also are important in determining the pattern of nuclei.) The overlapping of the QCD scale and the weak scale is a puzzle for fundamental theories which is distinct from the issue of fine-tuning. In the context of low-energy supersymmetry, if it exists, these considerations can be rephrased as the answer to the question of why, out of all the available parameter space, SUSY breaking takes place so close to the QCD scale.

There has recently been a work which helps to strengthen this result by pointing out that the production of the carbon would not have been possible if the Higgs vev was modestly smaller than observed.[7]

4. Comments on anthropic constraints

The above constraints are examples of reasoning that goes under the name of "the anthropic principle". There is a large and varied literature on anthropic ideas. This includes works of a technical nature, of which an excellent survey is found in the book of Barrow and Tipler[8], as well as those that provide thoughtful discussions[9]. The treatments above provide a different emphasis on ideas that appear throughout this literature, with a focus on the present key problems of particle physics. Much of the literature on anthropic ideas uses a narrow definition of life, one centered closely on life as we know it. The analyses which I described attempt to choose a much looser definition of the conditions relevant for the possibility of life (clumping of matter and the presence of complex elements). They also consider a much wider variation of the parameters, and attempt to calculate *typical* values of the parameters.

One of the criticisms of anthropic arguments is that they are just a way to get around making real testable predictions. Such abuse is always possible, but that is not really the point of such studies.

Rather, one is interested in understanding which questions are fruitful to consider.

Much of the research in particle theory beyond the Standard Model is driven by the fine-tuning problems. The assumption that supersymmetry is present down to low energies seems to have permeated the field. However, this could turn out to be wrong - which is why we must do the experiments to test it. The present indications of the existence of a cosmological constant should give us all some concern about fine-tuning arguments. Here is a de-facto fine tuning which does not appear to be solved by having new physics at the relevant scale. The anthropic considerations discussed above might be interpreted as the possibility that the fine-tuning problems are *not* the most important ones facing us§.

5. The weight for quark masses

If the quark masses are also parameters that can vary in different domains, then attempts to predict the specific values of the masses will not be fruitful. However the masses that we see are not really random. For example, there are more light masses than really heavy ones. It is not necessarily the case that the mass spectrum should be flat if they are variable. They may be distributed with respect to some weight. The interesting feature is that the residual information about the underlying theory is not in the specific masses, but in the weight. In such theories, the weight can be used as a test of the theory.

The observed weight in our domain has an intrinsic uncertainty since we only have information on 6 quark masses and 3 lepton masses. (I am assuming here that the physics of neutrino mass must be treated separately.) Nevertheless, when one tries to extract the weight from the data, it is remarkable that the uncertainty is not so great[10]. The answer can be summarized by saying that the weight is approximately the scale invariant form proportional to 1/m. (More precisely, the inverse power can vary between roughly 0.85 and 1.) If multiple domain theories are what occurs in nature, this can be a hint as to the structure of the correct theory.

6. Comments

At present, the ideas described above amount to little more than a "story" about how the theory could work. There has been little effort devoted to dynamical mechanisms. The example of chaotic inflation shows that it is indeed possible for physical parameters to be fixed at a continuous range of values. However it is not known how widespread this mechanism is in other theories. Certainly cosmology is the primary setting to explore the effect. In cosmology, causally disconnected regions in the early universe will have different conditions, and hence the initial conditions may possibly lead to different parameters. The implementation of these ideas in fundamental theories is an interesting challenge.

§ Note however that anthropic constraints cannot "solve" the strong CP problem. The Θ parameter is many orders of magnitude smaller than its viable mean value, and we need to seek a dynamical explanation for this.

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